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A burst from the direction of UZ Fornacis with *XMM-Newton*

Martin Still[1] and Koji Mukai[1]

NASA/Goddard Space Flight Center, Code 662, Greenbelt, MD 20771

ABSTRACT

The *XMM-Newton* pointing towards the magnetic cataclysmic variable UZ For finds the source to be a factor $> 10^3$ fainter than previous *EXOSAT* and *ROSAT* observations. The source was not detected for the majority of a 22 ksec exposure with the EPIC cameras, suggesting that the accretion rate either decreased, or stopped altogether. However a 1.1 ksec burst was detected from UZ For during the observation. Spectral fits favour optically thin, $kT = 4.4^{+7.6}_{-1.8}$ keV thermal emission. Detection of the burst by the on-board Optical Monitor indicates that this was most probably an accretion event. The 0.1–10 keV luminosity of $2.1^{+0.6}_{-0.3} \times 10^{30}$ erg s^{-1} is typical for accretion shock emission from high state polars and would result from the potential energy release of $\sim 10^{16}$ g of gas. There is no significant soft excess due to reprocessing in the white dwarf atmosphere.

Subject headings: binaries: close — stars: accretion — stars: individual: UZ For — stars: magnetic fields — stars: white dwarfs — X-rays: binaries

1. Introduction

Polars contain a white dwarf with a rotation period synchronously locked to a binary orbit and which accrete magnetically-threaded material from a Roche lobe filling companion star (Kube, Gänsicke and Beuermann 2000). Long-term monitoring has revealed that many polars undergo a cycle of high- and low-states. High states are generally characterized by thermal emission in X-ray bands (Done, Osborne & Beardmore 1995), with cyclotron and illuminated companion star emission contributing at lower energies (Ferrario et al. 1989). In the lowest states, X-rays are not detected and both intrinsic emission from the companion star and a Zeeman spectrum from the white dwarf dominate, indicating that accretion has almost ceased (Ferrario et al. 1992). An *XMM-Newton* pointing finds the polar UZ For in a low X-ray state, except during a burst of duration 1.1 ksec. This type of behaviour has not previously been seen during X-ray pointings of low state polars, and we investigate whether the burst was the result of a discrete accretion event.

[1]Universities Space Research Association

After its detection in the *EXOSAT* archive (EXO 033319-2554.2; Giommi et al. 1987), UZ For was identified as an eclipsing polar with a 127 min orbital period (Osborne et al. 1988; Beuermann, Thomas and Schwope 1988). During high states, gas accretes onto a small fraction of the white dwarf surface through standing shocks above one or more surface pole caps, where the field strength has been measured at 53 MG by Rousseau et al. (1996). Shocked gas is heated to $\sim 10^8$ K and subsequently cooled by hard Bremsstrahlung (Beuermann, Thomas and Pietsch 1991), cyclotron emission (Berriman and Smith 1988) and Compton scattering (Done and Magdziarz 1998). Polars are detectable as soft blackbody sources either from hard X-rays thermalized by the surface of the white dwarf (Ramsay et al. 1993; see also Ramsay, Cropper and Mason 1996), or diffused through the atmosphere after dense bullets have penetrated below the photosphere (Kuijpers and Pringle 1982). The diffusion model is preferred for UZ For because the combined Bremsstrahlung and cyclotron luminosity is not sufficient to power the soft X-ray component through thermalization (Frank et al. 1988; Ramsay et al. 1993). A thorough review of mag-

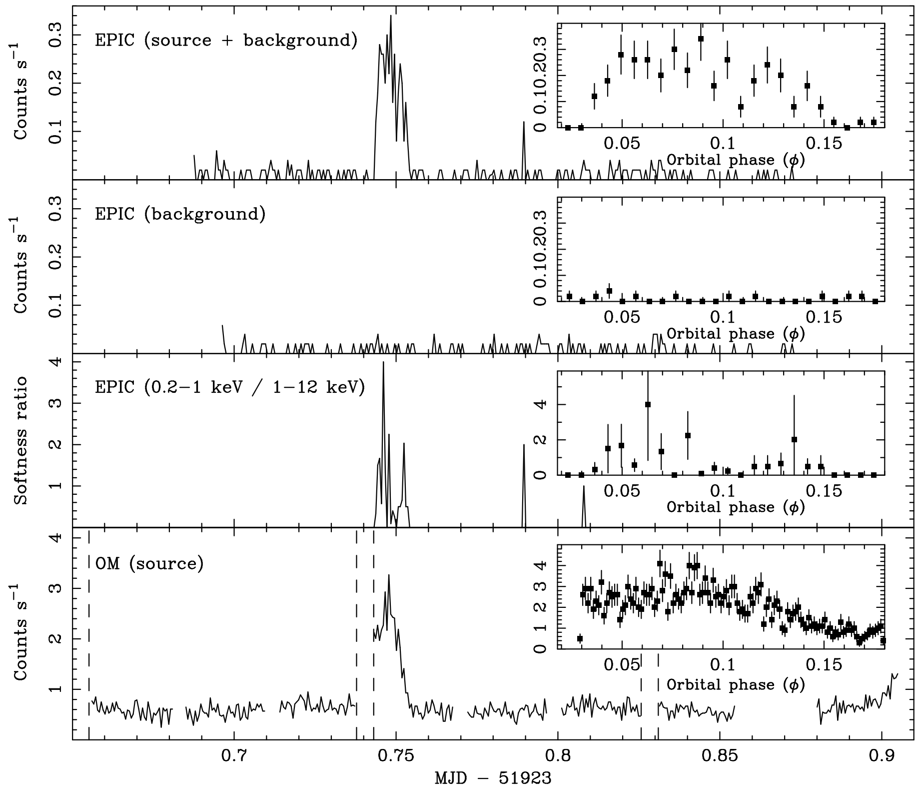

Fig. 1.— The top panel provides the MOS+pn source and background count rate, binned into intervals of 50 sec. The second panel is the MOS+pn background count rate and the third panel the softness ratio. The bottom panel displays the background-subtracted OM source count rate. The insets provide a blow-up of the burst, binned over the orbital ephemeris of Perryman et al. 2001. The OM inset is sampled at 10 sec. Dashed lines correspond to eclipse ingress and egress.

netospheric interaction, accretion dynamics and emission processes is given by Warner (1995).

2. Observations

XMM-Newton (Jansen et al. 2001) observed UZ For during the Performance Verification phase of telescope commissioning on 2001 Jan 14. The EPIC MOS, EPIC pn, RGS and OM detectors were all open during the pointing. The EPIC CCDs were configured in Large Window Mode and were integrated over 19 ksec (MOS1 and MOS2) and 22 ksec (pn). EPIC events were re-reduced using the standard pipelines within the *XMM-Newton* Science Analysis System (SAS) version 5.1, using the Calibration Access Layer current at 2001 July 3. Both RGS detectors were configured in spectroscopy mode but no detection of UZ For was found in reduced RGS events over integrations of 22 ksec. Eight consecutive exposures of 2.2 ksec were made by the OM in timing mode with the 240–360nm UVW1 filter.

2.1. Light curve

To reduce background from both MOS and pn cameras, single events were selected with corrected pulse heights > 200 eV from within a circular aperture of radius 23 arcsec, centered on the source. Background events were selected from an aperture of the same size, centered at an arbitrary source-free region, on the same chip as the target. Events from all three cameras were combined and total source and background light curves are presented in Fig. 1 with a sampling of 50 sec. Event arrival times have been corrected to the solar system barycenter.

For a large fraction of the pointing, the count rates from within the aperture are consistent with diffuse background. From the model of Ramsay et al. (1993; based on *ROSAT* high-state observations), consisting of a moderately absorbed 28 eV blackbody with a hard Bremsstrahlung tail, we expect a total of 3.1 events per second from the EPIC detectors. Unless accretion emission was arriving outside the EPIC bands (i.e., the accretion temperature was cooler), UZ For was caught during

a deep low state. Given the observed background rate, a 3-σ detection would require 10^{-3} counts s^{-1} in the aperture. Therefore the X-ray flux is generally $> 2.8\ \times 10^3$ times fainter than during the *ROSAT* pointing in the 0.1–2.0 keV band.

However, for a duration of 1.1 ksec, centered at MJD 51923.75, *XMM-Newton* detected a burst from the direction of UZ For. A sliding-box source detection algorithm provides 2000 sky coordinates of RA = $03^h35^m28^s.69(4)$, $\delta = 25°44'23''.4(6)$, in excellent agreement with the optical counterpart of UZ For (Downes and Shara 1993). The bracketed numbers are 1-σ uncertainties on the last digit. Time-dependent softness ratios were constructed using the bandpassses 0.2–1 keV and 1–12 keV. The ratios were set to zero in time bins unpopulated by hard events. Softness behaviour (also presented in Fig. 1) is constrained by low-number statistics, but gives the impression that the rise and decay of the burst are characterized by a soft spectrum which hardens during the peak of the event.

The UV counterpart to the burst was detected by the OM over a relatively constant number of source counts, probably intrinsic to the companion star. Since the OM timing analysis software is not currently available, OM events were extracted from the event files without pointing corrections or grade selection. The start times for each exposure were taken from the Non-Periodic Housekeeping file with an uncertainty of 1 s. Source and background apertures were both circular regions of radius 7 detector pixels. Note that the OM counts increase by a factor 2 at the end of the pointing, after the EPIC cameras have been turned off, perhaps indicating the onset of another event.

2.2. Energy spectrum

Ramsay et al. (1993) found a small hard X-ray excess in a *ROSAT* PSPC pointing of UZ For which they interpreted as Bremsstrahlung emission, however the majority of flux was confined to the soft energy bands and fit acceptably by a blackbody of ~ 28 eV. In this section we will attempt to fit similar models to the burst spectrum. We note that the softness ratio from Fig. 1 possibly indicates spectral variability during the burst, but small-number photon statistics prevent us from conducting time-dependent spectral fitting.

Single source events with pulse heights > 100 eV were selected within the time range MJD 51 923.7435–51 923.7562, from the same sky region as in Sec. 2.1. Background count rates are 1.2×10^{-3} counts s^{-1} in the MOS cameras and 4.8×10^{-3} counts s^{-1} in the pn camera within the defined filter region, i.e., there are ~ 2 and 6 background events contaminating the source spectrum of each MOS and the pn cameras, respectively. Since both the source and background are subject to low-number statistics, we do not subtract a background spectrum.

Events were binned spectrally to provide a signal-to-noise > 5 and 10 in each channel of the MOS and pn detectors, respectively. MOS1, MOS2 and pn spectra were folded through appropriate response files and fit together using a maximum-likelihood scheme (Cash 1979) with a single blackbody model, absorbed by a neutral column. A C-statistic of 42.3 over 22 spectral bins indicates a blackbody of 440^{+60}_{-50} eV with a flux of $2.9^{+0.5}_{-0.4}\times10^{-13}$ erg s^{-1} cm^{-2} and negligible neutral absorption. This is hotter than expected from thermal emission on the white dwarf surface (e.g., Ramsay et al. 1993). A Monte Carlo test, using 1000 realizations, created fake spectra based on the best model parameters and the observed counts. This successfully produced an improved fit over the data for 99.7 percent of the realizations. Therefore the model is not a good fit statistically.

With a C-statistic of 21.8 over 22 spectral bins, a $4.4^{+7.6}_{-1.8}$ keV Bremsstrahlung model, absorbed by a neutral column of $3.2^{+2.5}_{-1.8}\times10^{20}$ cm^{-2}, provides an acceptable fit. The Monte Carlo test provided an improved fit over the data with 48.8 percent of 1000 realizations. The neutral hydrogen column density through the galaxy in the direction of UZ For is $1\ \times10^{20}$ cm^{-2} (Dickey and Lockman 1990). The emission measure is given by $\int n_e^2 \mathrm{d}V = 4.3^{+1.3}_{-0.6}\times10^{11} D^2$ cm^{-3}, where D is the source distance, n_e the fully-ionized electron density, and V the emitting volume. Data and fits from the MOS2 and pn cameras are presented in Fig. 2.

Although the MOS2 data show a possible excess in the softest channel, a fit of absorbed Bremsstrahlung and blackbody components, combined over all three EPIC detectors, results in a blackbody of negligible intensity, yielding no improvement in fit quality. Fits of greater sophistication (e.g., multi-temperature shocks and Compton

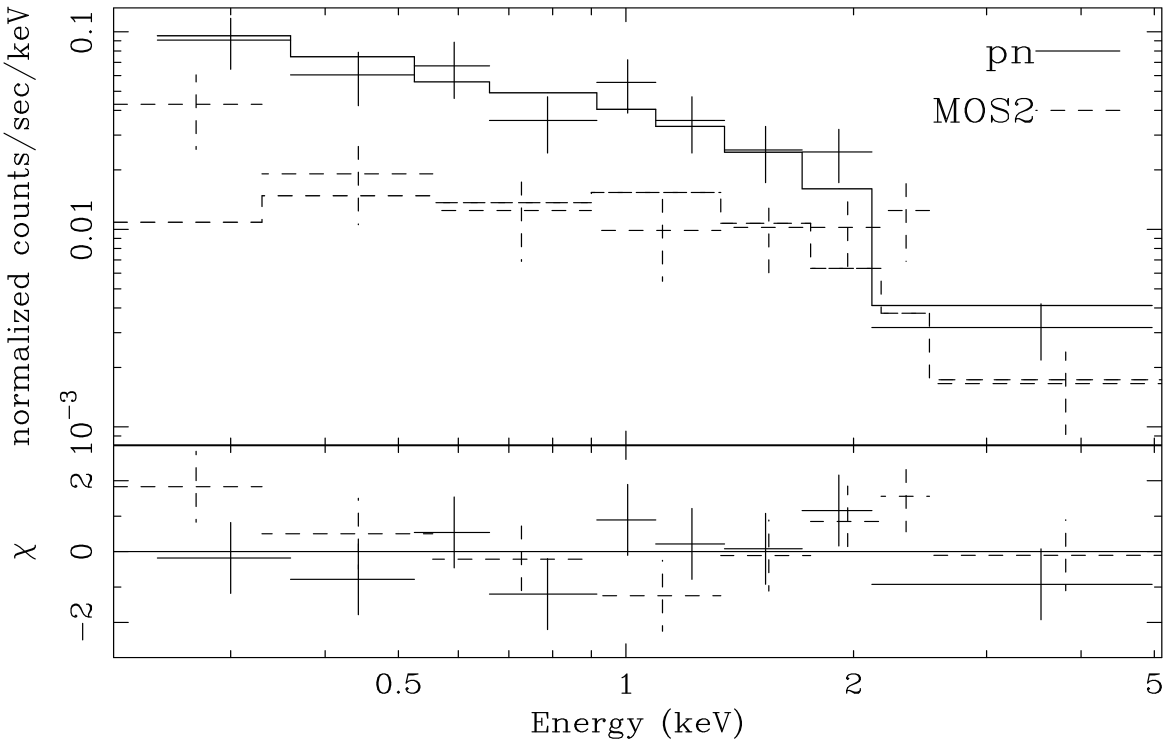

Fig. 2.— Energy spectra for the EPIC MOS2 and pn cameras. The MOS1 spectrum has not been included for presentation clarity. Energy channels have been binned so that signal-to-noise in each channel is > 5 (MOS2) and > 10 (pn).

cooling; Ramsay et al. 2001) are not justified by the data.

3. Discussion

Two similar bursts, of duration $\sim$ 1 hr, were observed during an otherwise non-detection of the polar QS Tel using *EUVE* by Warren et al. (1993). Using the family of solutions that Warren et al. were able to constrain, the Bremsstrahlung emission observed during the UZ For burst is at least an order of magnitude fainter than the QS Tel events.

Adopting a distance to UZ For of 208 $\pm$ 40 pc (Ferrario et al. 1989), the emission measure is $8.7^{+2.6}_{-1.2} \times 10^{52}$ cm^{-3}. This is consistent with flares from rapidly rotating M dwarfs, similar to the companion star, which show typical emission measures of 10^{52-54} cm^{-3} (e.g., Pan and Jordan 1995; Pan et al. 1997). The derived electron temperature is also typical of coronal activity on late-type stars ($\sim 10^7$ K; Pan and Jordan 1995). Stellar flares are generally characterized in two classes which, like the current burst, soften spectrally at the beginning and end of each event (Tsikoudi and Kellett 2000). Long-decay flares have similar soft spectra to the UZ For event, but with decline times of the order a few hours. Impulsive flares have rapid rise and decay times similar to the present burst, but generally have shorter lifetimes and harder spectra (> 20 keV; Schmitt, Haisch and Barwig 1993). The UZ For burst fits into neither category.

However, the UV detection of the burst indicates the event is unlikely to be coronal in origin, but UV emission is a predictable consequence of white dwarf accretion (e.g. Warner 1995). Without simultaneous low-energy observations, the nature of the burst would have remained ambiguous. This event illustrates the advantages of flying optical/UV detectors on-board high energy missions. Again assuming a distance of 208 pc, the 0.1–10 keV burst luminosity is $2.1^{+0.6}_{-0.3} \times 10^{30}$ erg s^{-1}. This is consistent with the typical hard X-ray luminosities of high state polars (Chanmugam, Ray and Singh 1991). Assuming that all the ac-

cretion energy is emitted in the EPIC bands, then $L_X = G\dot{M}M_{WD}/R_{WD}$. L_X is the X-ray luminosity, G the gravitational constant, $\dot{M}$ the mass accretion rate, M_{WD} the white dwarf mass and R_{WD} the white dwarf radius. If we consider a 1 solar mass white dwarf of radius 10^9 cm, the mass accretion rate is 1.6 $\times 10^{13}$ g s^{-1}. 1.7 $\times 10^{16}$ g of material will have been accreted during the burst.

We find no statistically-significant evidence for a soft spectral component due to white dwarf reprocessing. Consequently, the accretion density must be relatively low in order to prevent gas piercing below the white dwarf photosphere (Frank et al. 1988). However illumination from above by the shock should result in a photospheric blackbody temperature of $\sim$ 20 eV, which would be detectable in the softest channels of the EPIC detectors (e.g., Beuermann, Thomas and Pietsch 1991). Similarly, *XMM-Newton* observations of WW Hor in an intermediate accretion state find no evidence for a soft component. (Ramsay et al. 2001) argue that this could be the consequence of a larger-than-usual accretion zone, resulting in reprocessed emission too cool to be detected with the EPIC cameras.

To check the visibility of the major accreting pole on UZ For during this burst, we fold the data over two orbital ephemerides measured from optical eclipse timing. The ephemeris of Perryman et al. (2001) indicates that the burst begins at ϕ = 0.03–0.04, where ϕ = 0.000 is defined as superior conjunction of the white dwarf. At this phase the main high-state accretion spot is on the visible side of the white dwarf. However this also corresponds to the egress phase of white dwarf eclipse which occurs rapidly over 1–3 s in optical bands. The characteristic scatter of eclipse times about this ephemeris is large, $\sim$ 50 s, possibly indicating systematics caused by a migrating accretion spot. However it is plausible that the perceived start of the burst is in fact eclipse egress, and the burst started, in reality, during white dwarf eclipse. Consequently, the intrinsic burst may have been up to 450 s longer than observed. From an eye inspection of the EPIC event list, the first detected X-ray photon that may be associated with the burst was received at MJD 51923.7438. Since this is 8×10^{-3} of an orbital cycle after eclipse egress, there is no evidence that the burst was visible during eclipse. The X-ray and UV bursts, binned on the orbital phase are presented in the insets to Fig. 1. The rise to UV burst occurred within a 10 s period, consistent with the optical eclipse egress. Although statistically the X-ray and UV bursts started simultaneously, there is some suggestion (albeit based on low-count statistics) that the X-ray burst takes somewhat longer to rise.

Unfortunately, the OM data gaps coincide with each white dwarf eclipse (Fig. 1). Therefore there are no spatial constraints on the source of the low-state UV flux. Extrapolation of the models of Houdebine et al. (1996) indicate that the luminosity from an M dwarf of radius 0.2 $M_\odot$ could be as large as 2 $\times 10^{29}$ erg s^{-1} in the UVW1 bandpass, although there is some ambiguity due to the nature of chromospheric structure. This predicts a maximum companion star flux of 4 $\times 10^{-17}$ erg s^{-1} cm^{-2} Å^{-1}. Neglecting CCD readout deadtimes (which are currently unavailable), the OM count rate indicates a source flux of 3 $\times 10^{-16}$ erg s^{-1} cm^{-2} Å^{-1}. Therefore, in the absence of an accretion stream, a large fraction of the low-state UV flux must have a source on the white dwarf, where the flux is reasonable for a white dwarf of radius 10^9 cm, emitting like a blackbody at 20 000 K. At its peak, the UV flux in the burst is 1.4 $\times 10^{-15}$ erg s^{-1} cm^{-2} Å^{-1}, neglecting deadtime. With a surface magnetic field of 53 MG, we do not expect cyclotron emission in the UVW1 passband. Therefore it is likely the UV burst occurs in the heated polar cap of the white dwarf (c.f. Gaensicke et al. 1998).

4. Conclusion

During a low accretion state of the magnetic cataclysmic variable UZ For, *XMM-Newton* detected a burst with a duration of 1.1 ksec. The event is best characterized by an absorbed Bremsstrahlung spectrum, with the temperature possibly directly correlated with intensity. This suggests that the emission region is either a coronal flare from the companion star, or a standing shock above the magnetic pole of the white dwarf. The temperature, emission measure and colour evolution of the burst are consistent with a stellar flare, however the brightness variability and spectral shape do not fit conveniently into either class of long-decay or impulsive flares. Detection

of a UV counterpart to the X-ray burst strongly suggests that this is an accretion event, where the 0.1–10 keV luminosity is of the same order as the mean Bremsstrahlung luminosity of high state polars. The burst timing suggests that it is associated with the pole that dominates accretion during high states and that the event may have begun during white dwarf eclipse.

This behaviour has not been found previously in polars, although the EUVE counterparts of similar events may have been detected by Warren et al. (1993). As a conjecture, this burst may be indicative of occasional, but significant, amounts of companion star gas falling through the L_1 point of the binary during low accretion states. If similar events were detected in the future, it would be interesting to correlate this activity with the long term high/low state accretion cycle. Perhaps the frequency of these events indicate impending switches from the low to high state.

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